INTRODUCTION

Coastal wetlands worldwide are increasingly valued for buffering the capacity of coastal storms to flood or erode uplands, filtering urban runoff, providing wildlife habitat, and supporting coastal fisheries (Beatley, Brower, and Schwab, 2002). Rapid development of coastal regions has led to the establishment of an array of local, state, and national regulatory efforts to protect these ecosystem functions. Among the national programs in the United States which support conservation of coastal wetlands is the National Estuarine Research Reserve (NERR) system.

The NERR program was created by the Coastal Zone Management Act of 1972 (National Estuarine Research Reserve System, 2004) to encourage "long-term research, water-quality monitoring, education, and coastal stewardship" (Guana Tolomato Matanzas Reserve, 2004, February 18). The reserves constituting the system are selected from areas nominated by states to represent distinct biogeographic regions. The National Oceanic and Atmospheric Administration (NOAA) provides a maximum of 70% of funding for reserve operation and state partners are responsible for providing a minimum of 30%. The federal government relies on the states to provide resource management to "ensure a stable environment for research" (National Estuarine Research Reserve System, 2005(a)). NOAA is authorized to withdraw the designation of a reserve if a stable research environment is not maintained (National Estuarine Research Reserve System, 2005(b)). This study addresses an issue which has the potential to threaten the stable research environment of the Guana Tolomato Matanzas National Estuarine Research Reserve (GTMNERR)— the issue of habitat degradation due to erosion along the margin of the Atlantic Intracoastal Waterway (AICW). Not only is such habitat degradation an issue of concern given the reserve management objectives, but it also is in conflict with the desired trend of "no net loss of wetlands" supported by local regulations (Flagler County, 2004) and federal commitments (U.S. Environmental Protection Agency, 2004).

The GTMNERR is divided into two sections, together comprising approximately 24,000 hectares (60,000 acres) in St. Johns and Flagler counties in northeastern Florida. The Guana, Tolomato, and Matanzas Rivers are the major estuarine bodies of the reserve; together they form a string of relatively narrow "bar bounded" estuaries behind the barrier islands which line the Atlantic coast. This study focuses on the AICW in the southern portion of the GTMNERR (Fig. 1). The AICW in the study area consists of a marked channel in the Matanzas River, portions of which have been deepened and straightened to provide enhanced navigation, and portions of which are completely man-made channel.

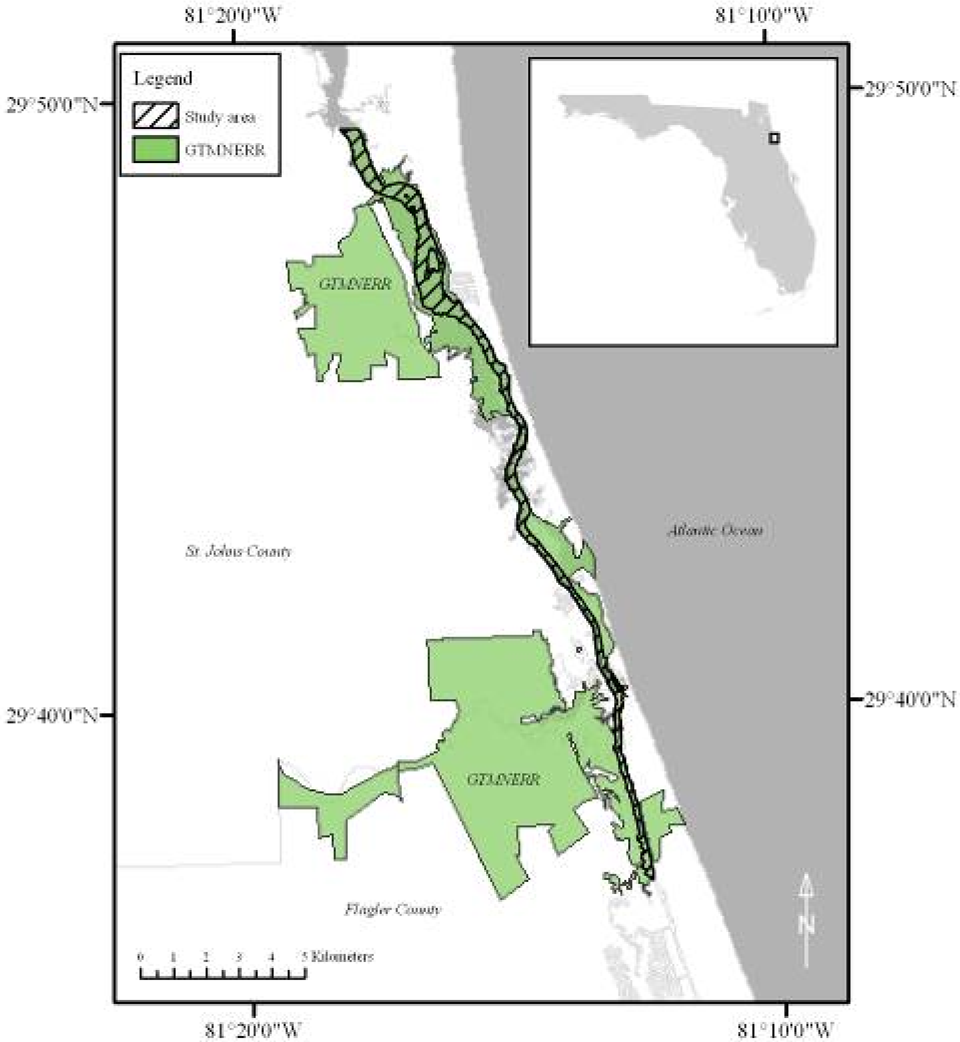

Fig. 1: Study area – Southern portion of Guana Tolomato Matanzas National Estuarine Research Reserve (GTMNERR)

Habitats found in the reserve include salt marsh and mangrove tidal wetlands, oyster bars, estuarine lagoons, creeks and rivers, dredge spoil disposal areas, upland, and a section of the adjoining Atlantic Ocean. It is of interest that the mangrove wetlands in the reserve constitute "the northern-most extent of mangrove habitat on the east coast of the United States" (Guana Tolomato Matanzas Reserve, February 18, 2004). The hydrology of GTMNERR estuaries has been significantly altered by human activities, including the construction of the AICW (Guana Tolomato Matanzas Reserve, 2004, February 18) which was first dredged as early as 1883 (Florida Inland Navigation District, 1967).

Years of personal observations and a brief pilot study conducted in the fall of 2003 made apparent the process of erosion and subsequent habitat degradation in the GTMNERR. The high rate of erosion observed in the GTMNERR appeared to be degrading natural habitats at a rate far faster than they could rebuild. Studies have shown that lateral erosion of salt marsh channels, such as that of the AICW and its tidal tributaries, is naturally offset by deposition in other areas (Letzsch and Frey, 1980). Thus, any observation of widespread erosion not offset by accretion elsewhere, warrants careful examination.

The margin of the AICW channel which runs through the reserve has eroded considerably over the past thirty years. As a result, highly productive habitats, including salt marsh, mangroves, and oyster bars, have been eroded and replaced by intertidal sand flats which are considerably less productive (Montague and Wiegert, 1990) and thus, potentially less valuable from an ecological perspective. The channel of the AICW in the GTMNERR is lined with tidal creeks, oyster bars, salt and mangrove marshes, dredge spoil islands, and developed uplands. The intent of this study is to (1) quantify the extent of habitat loss due to channel margin erosion from 1970 to 2002, (2) examine correlations between erosion rates and possible causal factors, (3) investigate management alternatives which could be used to limit erosion linked degradation at the AICW margin, and (4) examine the regulatory framework surrounding the implementation of such alternatives. Evidence suggests that boat wakes are the primary cause of observed erosion.

Background

The process of habitat loss to erosion in the GTMNERR can be described as erosion along the margin of a major estuarine channel which has been modified to provide for navigation. As displayed in Figure 2, the primary forces responsible for the movement of sediment are waves, currents, and human dredging and filling. Sediment supply regulates the amount of sediment available for accretion, and the sediment type and level of biological stabilization or destabilization govern the mobility of channel margin sediments. Of these factors, several can be disregarded as potential causes of the erosion in the GTMNERR and several are likely contributing causes. The role of sea level change is also addressed due to its connection to the global climate change debate and by association its application to coastal erosion.

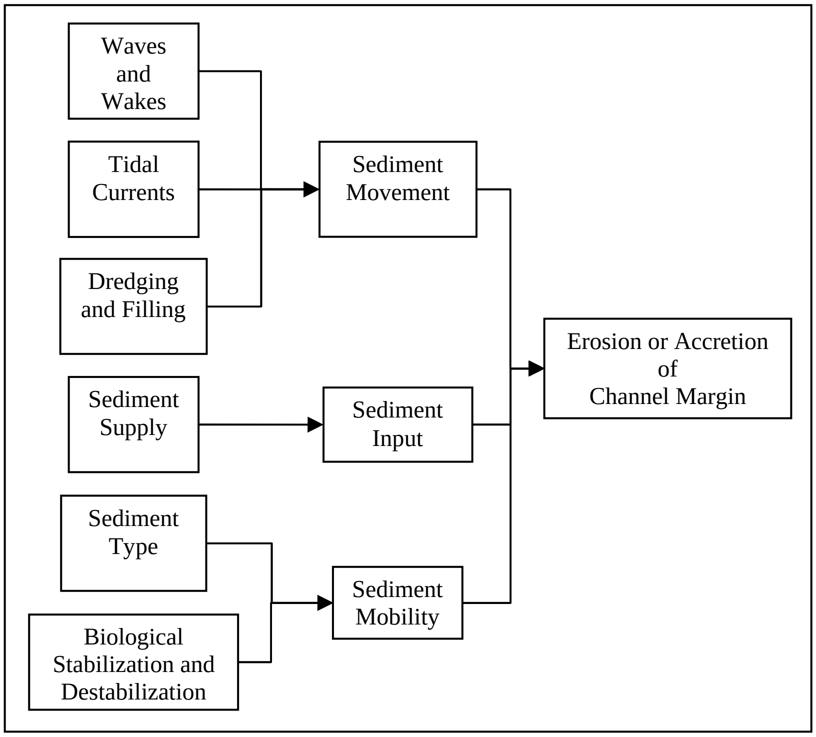

Fig. 2: Factors affecting erosion and accretion along an estuarine channel margin

Waves and wakes

In estuarine systems, the two major sources of wave energy are wind waves and boat wakes. Both are recognized as capable of causing significant sediment transport in a variety of aquatic environments.

Wind waves are cited as a cause of marsh erosion in a number of studies (Phillips, 1986b; Downs, Nicholls, Leatherman, and Hautzenroder, 1994; Day, Scarton, Rismondo, and Are, 1998; Doane, Wells, and Merman, 1998; Schwimmer, 2001). Waves erode the accumulation of peat under the stabilizing root mat of smooth cordgrass, *Spartina alterniflora*, the dominant marsh vegetation in the GTMNERR. This results in the episodic collapse of blocks of the marsh at the fringe. The unconsolidated sediments of non-marsh channel margins erode in a less sporadic manner. The prediction of the extent of wind wave erosion is difficult due to the number of factors which influence wave energy at bank impact. These factors include wind speed, duration and fetch (distance that winds blows over water), as well as water depth, influence of currents and angle of wave impact. Previous studies (Hershberger and Ting, 1996) have shown that even complex models of inshore wave propagation can encounter considerable error. Hershberger and Ting's research in the Gulf Intracoastal Waterway compared field measurements of wave height and period with those predicted by the U.S. Army Corps of Engineers (USCOE) Automated Coastal Engineering System model and found the model to over-predict waves when wind was blowing along the channel and under-predict waves when wind was blowing across the channel. Considerable expertise is necessary to accurately predict wind wave-caused erosion through the prediction of wave energy in a channel such as the AICW. A simpler predictor of channel margin erosion may be the presence or absence of exposure to causal factors such as wind waves.

Wind wave erosion has been found to be most severe downwind of the prevailing wind and largest local fetch (Downs et al., 1994; Day et al., 1998; Doane et al., 1998; Schwimmer, 2001). NOAA data from a coastal automated weather station approximately 2 km east of the study area show the predominant direction of winds over 10 knots from 1986 to 2001 to be from the north at 345^o to 45^o (National Oceanographic and Atmospheric Administration, 2003). The Beaufort wind scale defines 10 knots as the wind velocity at which small waves generally start to form and thus wind wave erosion can be expected to begin to occur. The severity of erosion can be expected to increase with increasing wind speed and storm events have the potential to cause rapid erosion.

During the study period northeast Florida experienced relatively few cyclonic storms. From 1970 to 2002 only 17 tropical systems passed within 65nm of Marineland, FL (the approximate center of the study area). Of these storms only one was a hurricane, eight were tropical storms, three were tropical depressions, two were subtropical storms, two were subtropical depressions and one was a tropical low. Only two storms impacted the northeast Florida coast directly, six passed offshore and nine made landfall elsewhere in Florida and exited into the Atlantic along the northeast coast. The three most powerful storms, Hurricane David in 1979, Tropical Storm Bob in 1985, and Tropical Storm Diana in 1984, with wind speeds of 85, 60 and 60kts respectively, all passed offshore. This suggests that their winds would come from a northerly direction like the predominant winds over 10 knots.

From 1986 through 2001 (the only portion of the study period for which local wind data is available) the northeast quadrant was not only the predominant direction for wind over 10kts, 59.7% of winds over 16kts were from the northeast, 77.8% of winds over 21kts were from the northeast and 90.9% of winds over 25kts were from the northeast (National Oceanographic and Atmospheric Administration, 2003). During this period, the study area was impacted by two tropical storms, three tropical depressions, a subtropical depression and a tropical low. Northeast winds were dominant during storm conditions as well as average conditions. This justifies the assumption that wind wave erosion along the Matanzas River will be most severe downwind of northeast winds, or along river channel margins facing north, from 90 to 300 degrees.

Boat wakes are also widely recognized as a cause of bank erosion in inland bodies of water (Zabawa, Ostrom and Byrne, 1980; Williams, 1993; Grossfeld, 1997; Maynord et al., 2001; Wilcox, n.d.; Kennish, 2002; Raines, 2003). Factors influencing the erosive impact of boat wakes include size of the generated wave, water depth, current direction and velocity, morphology of the impacted bank, presence of wind waves, and distance of the vessel from the shore (Macfarlane and Renilson, 1999). The size of the wake is governed by vessel speed, hull form, draft, loading, and trim. Generally, fast moving vessels displacing large volumes of water produce the largest wakes while vessels displacing less water and moving slowly or at planing speed produce the smallest wakes.

Wake-caused erosion can be distinguished from wind wave-caused erosion in that it occurs in areas sheltered from wind waves and may be most severe where the AICW channel is closest to the channel margin. Wakes can be expected to be a much more significant problem in the GTMNERR than in wider bodies of water. The relatively narrow channel of the AICW does not allow significant distance for wake energy to subside before wakes impact the margin. The narrow channel also does not provide as large a fetch for the development of wind waves as wider channels do; thus, ecosystems along the margins of the AICW are adapted to significantly lower energy levels than those along channels where larger wind wave propagation is possible. Personal observations supported by consultation with knowledgeable locals and experts in the field of coastal geomorphology (Sergio Fagherazzi, personal communication, 2004) have led to the hypothesis that boat wakes in the AICW are the primary case of channel margin erosion in the GTMNERR.

Tidal currents

Generally, river channels erode on the outside of bends, where current velocity and resultant shear stress is highest and accrete on the inside of bends. Tighter bends, with smaller radii of curvature, erode on the outside and accrete on the inside faster than wider bends with larger radii of curvature (Leopold, Wolman, and Miller, 1992). In stable systems lateral, current-induced erosion in one area is offset by accretion in another (Letzsch and Frey, 1980).

Dredging and filling

Dredging and filling for navigational or other purposes can cause erosion or accretion in several ways. Most obviously, channels can be dredged through an area or existing channels can be filled. This results in <u>apparent</u> erosion or accretion in a map or aerial photograph. According to Brian Brodehl of the USCOE Jacksonville district (personal communication, September 10, 2004), dredging can also cause channel widening when a channel is dredged to such a depth that when channel bed sediments reach their natural angle of repose, the bank is under cut. If the dimensions of a channel and the angle of repose of constituent sediments are known, it is possible to calculate the potential for erosion due to this mechanism. Considering that the planned dimensions for the AICW navigation channel are 125 feet wide by 12 feet deep and that the approximate angle of repose of bed sediments is 1:2.5 (according to B. Brodehl), the current mean width of the entire tidal channel, over 1000 feet, is more than sufficient to accommodate the construction of the channel without under cutting banks. Mr. Brodehl acknowledged that although the USCOE considers this calculation in the dredging of the AICW channel, it is likely that historically dredging efforts were not as carefully engineered.

It is also possible for dredging to alter depth or fetch available for wave propagation, or to alter current direction or velocity and thus indirectly influence local erosion rates. One mechanism through which channel dredging may increase current velocities and increase erosion rates is through alteration of the tidal prism (the difference in the volume of water in a water body between low and high tides) (Cox, Wadsworth, and Thomson, 2003). It is likely that dredging associated with the creation of the AICW altered the local tidal prism, but it is difficult to determine the magnitude of the change or to relate this change to sedimentary processes.

A second manner in which navigation related dredging and filling may have affected tidal currents, and thus affected sedimentation, is through the alteration of natural channels in the vicinity of Matanzas Inlet, both during the initial construction of the AICW and again in the 1970's. Figure 3 allows the comparison of the modern channel configuration with the unmodified channel, as depicted in United States Coast Survey maps created in 1867 and 1872. The channel to the north of the inlet was realigned during construction of the AICW channel as was the smaller channel running south from the inlet. The thin strip of land dividing the inlet and the navigation channel was also fortified to prevent tidal currents from depositing sediment in the channel. Together these modifications dramatically altered the natural tidal channels in the vicinity of the inlet and are likely to have caused substantial changes in sediment transport processes.

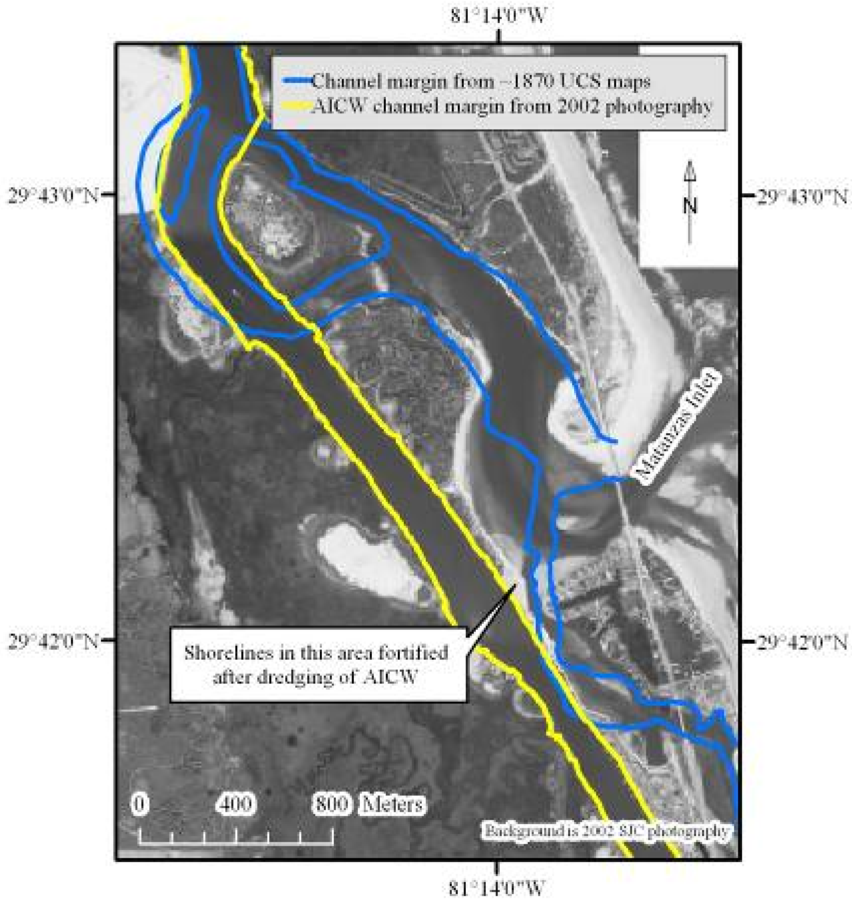

Fig. 3: Alterations in the vicinity of Matanzas Inlet

The precise effect of such alterations is again difficult to discern. However, a portion of the study area, from the State Road 206 Bridge to the north end of the study area, has apparently never been dredged (judging from the absence of dredge spoil islands) and can be viewed as a control for the examination of dredging impacts.

Sediment supply

The primary condition which must be met for accretion to occur is the existence of a sufficient supply of sediment. The primary sources of allocthonous sediment for most marsh systems are (1) riverine sources, (2) off-shore sources, (3) barrier wash-over, (4) erosion of coastal cliffs, and (5) wind-blown sediments. Biogenic organic aggregates provide the major source of autochthonous sediments (Frey and Basan, 1978). The AICW in the study area does not receive significant input of sediment from riverine sources or experience substantial barrier island wash over and is not located near any coastal cliffs. Off-shore sources, wind-blown sediments, and organic aggregates are most probably the major potential sources of new sediment (personal observations, 1980-present). Dredged bed sediment also may contribute considerably to the sediment supply, both during the dredging process and later as dredged sediment is reworked from shoreline disposal areas. There is no indication of a change in sediment supply levels during the study period.

Sediment type

Channel margin sediments in the study area vary from coarse oyster shells to fine organic sediments. This variation in sediment type can be coarsely represented by separating locations along the AICW channel margin into one of five different categories: intertidal bars, salt marsh, sandy dredge spoil disposal areas, uplands, or water (the mouths of tributaries or off-channel areas which join the main channel). Although these categories are not completely discrete and are somewhat subjective, they can be viewed as an indicator of both channel margin sediment type and the level of biological stabilization or destabilization. Intertidal bars contain mostly disarticulated oyster shells; marshes contain very fine sediments; spoil is generally sandy with some shell; uplands are sandy, but are usually reinforced with tree roots or seawalls. The 64.8 kilometers of channel margin examined in this study were classified as displayed in Table 1 below. Each sedimentary class can be expected to respond differently to erosive forces due to both the physical structure of the sediment and the levels of biological stabilization or destabilization.

Table 1: Summary of 1970/1971 channel margin classification

Margin classification	Margin length (km)	Proportion of margin length	Sediment Type
intertidal bars	8.7	13%	shelly
marsh	24.8	38%	mud / silt
dredge spoil	19.3	30%	sandy
upland	6.1	9%	variable
water	5.9	9%	N/A
Total	64.8	100%	

Biological stabilization and destabilization

Estuarine organisms can have both positive and negative influences on the stability of channel margins. The major species responsible for shoreline and nearshore stabilization in the GTMNERR are smooth cordgrass, *Spartina alterniflora*, and the eastern oyster, *Crassostrea virginica*. Atlantic coast salt marshes, such those found in the GTMNERR, commonly consist of extremely fine unconsolidated silts and clays (Frey and Basan, 1978), the top several inches of which are reinforced by the rhizomatic mat of *Spartina alterniflora* and associated peat deposits. Personal observations suggest that marsh erosion in the reserve follows the general pattern described in the seminal work of Redfield (1972). Erosion of the sediment from under the root mat / peat layer leaves the marsh surface unsupported and results in the mass wasting of large blocks of the vegetative mat and coherent sediment. This erosive process makes clear the fact that although *Spartina* roots do reinforce marsh sediments, they cannot prevent erosion in a high energy environment.

Oysters also protect fine marsh sediments from erosive forces and are not immune to damage from waves. Grizzle, Adams and Walters (2002) conducted a study of aerial photography in the Indian River Lagoon, on Florida's east coast, and observed widespread death of oyster bar margins, an occurrence they attributed to the action of boat wakes. Both wind waves and wakes have the potential to inhibit the settlement of larval oysters and physically move or smother adult oysters with sediment. Dead oyster bar margins similar to those discussed by Grizzle et al. (2002) are common in the GTMNERR. They appear much lighter in color than healthy bars and can be distinguished in aerial photographs. Informal analysis of aerial photos of the reserve suggests that all oyster bar margins with direct exposure to the navigation channel of the AICW could be classified as dead as indicated by their relatively light color.

Biological destabilization, or bioturbation, involves physical disturbance of sediment by living organisms, such as the fiddler crab, *Uca pugnax* (Letzsch and Frey, 1980). Fiddler crab burrows penetrate marsh sediments and thus increase their susceptibility to erosion by waves or currents. Although native organisms such as *U. pugnax* may decrease the stability of sediments in stable ecosystems, lateral erosion and deposition are roughly equal even in their presence (Letzsch and Frey, 1980). Thus, in the absence of any drastic ecosystem changes, bioturbation should not be viewed as a primary cause of erosion. The same holds true for other examples of ecosystem change with the potential to alter marsh erosion rates. Periwinkle snails, *Littorina sp.*, have been observed to feed on *Spartina*; and in the absence of predation by blue crabs, *Callinectes sapidus*, populations of snails may have the potential to devastate *Spartina* marshes, destabilizing sediments and lowering deposition rates (Bertness and Silliman, 2002). Again, overall sedimentation rates should not be expected to change significantly unless there is a substantial change in trophic structure.

Alteration of the trophic structure of an ecosystem can cause otherwise innocuous processes, such as bioturbation or predation, to have drastic effects on the stability of the system. However, determination of the role of such processes in marsh erosion is difficult due to the natural complexity of ecosystems and the large amount of observational data necessary to ascertain if a change is occurring. No major changes in trophic structure, with clear potential to alter erosion rates, have been reported in the GTMNERR.

The role of sea level

Relative sea level change at a shoreline can result from a change in eustatic sea level (the level of the global ocean in relation to the center of the earth) and / or change in the elevation of the local land surface relative to the center of the earth. Mean sea level is measured through analysis of tidal gauge data corrected to account for seasonal and interannual variation and change in land elevation. The lack of tidal data for any one location in the study area for any significant portion of the study period negates the possibility of conducting this type of analysis. However, a NOAA sea level trend analysis for a tidal gauge approximately 48 miles north of the study area reported an average rate of sea level rise of 2.43 mm y^{-1}, from 1928 to 1999, and a total rise of 7.78 from 1970 to 2002 (NOAA, n.d. a). This rate is at the high end of the range of the estimated current global average rate of sea level rise of 1.0 to 2.4 mm y^{-1} (NOAA, n.d. b).

Sea level rise has been implicated as a causal factor in a number of studies of marsh erosion (Phillips, 1986a; Salinas, DeLaune, and Patrick, 1986; Kearney, Grace, and Stevenson, 1988; Reed, 1988; Downs et al., 1994; Kastler and Wiberg, 1996; Day et al., 1998; Hartig, Gornitz, Kolker, Mushacke, and Fallon, 2002). In these studies, subsidence and eustatic sea level rise often function in concert to increase erosion rates; but in several locations including Venice, Italy (Day et al., 1998) and Louisiana, (Salinas et al., 1986) subsidence appears to be the underlying cause of observed erosion. Subsidence is the decrease in elevation of the land surface due to extraction of subsurface resources or geologic processes. There have been no recorded observations of subsidence in the reserve.

In cases of erosion exacerbated by eustatic sea level rise and those involving subsidence, the response of the marsh appears to be essentially the same. A simplified relationship of marsh elevation to relative sea level was presented by Redfield (1965), who found that if salt marsh surface accretion keeps pace with relative sea level rise, then the marsh will remain stable. This view was amended by Orson, Panageotou, and Leatherman (1985) and again by Schwimmer and Pizzuto (2000) who studied a rapidly eroding marsh in which the aggradation (vertical building) rate exceeded the rate of relative sea level rise. Schwimmer and Pizzuto propose that in the face of relative sea level rise a marsh can either (1) erode (retreat laterally), (2) prograde (build laterally), or (3) drown depending on local rates of relative sea level rise and marsh surface and nearshore sedimentation rates. Nearshore sedimentation is critical because it has the potential to alter bathymetry and thus affect the erosive impact of waves.

A marsh shoreline erodes, in the presence of relative sea level rise, when the nearshore sedimentation rate is less than the local rate of relative sea level rise and the rate of marsh aggradation is greater than the rate of relative sea level rise (i.e. the marsh builds upward fast enough to stay above water but erodes laterally). A shoreline progrades, in the presence of relative sea level rise, when the nearshore sedimentation rate and the rate of marsh aggradation are both greater than the local rate of relative sea level rise (i.e. the marsh not only builds upward fast enough to stay above water, but high nearshore deposition rates allow it to build laterally). A marsh drowns when the near shore sedimentation rate and the rate of marsh aggradation are both less than the local rate of relative sea level rise (i.e. the marsh cannot build upward fast enough to stay above water). The first indicator of drowning is the deterioration of the vegetative marsh mat due to excessive inundation. Where mat deterioration occurs, new areas of open water form and are then enlarged by waves in the direction of the predominant wind (Stevenson, Kearney, and Pendleton, 1985).

Considering these statements, if, in the presence of relative sea level rise, erosion is observed but drowning is not observed, as is the case in the GTMNERR, the marsh must be aggrading and erosion must therefore be caused by relatively low nearshore sedimentation rates. Nearshore sedimentation rates are influenced by wave climate and sediment supply (Schwimmer and Pizzuto, 2000), so erosion can be expected to be most severe in locations where sediment supply is lowest and wave energy is highest. Due to this relationship, sea level rise should not be considered a primary cause of erosion, but rather a secondary factor with the potential to increase the rate of erosion due to waves or nearshore currents.